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Nervous system drugs taken by future fathers and birth defects in offspring: a registry-based cohort study

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Keywords

Birth defects, congenital anomalies, congenital malformations, paternal effects, drug safety

Ethical approval

This article uses existing registry data (from Denmark), which are exempt from IRB review given that the data are deidentified.

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Abstract: 293 words
Main text: 2,127 words

Abstract

Objectives

To evaluate the association of paternal preconception intake of antipsychotics, anxiolytics, hypnotics and sedatives, antidepressants, SSRIs, and (benzo)diazepines with birth defects in offspring.

Design

Registry based cohort study

Setting

Total Danish birth cohort 1997-2016 using Danish national registries

Participants

All 1,201,119 Danish liveborn singletons born 1997-2016 were included, 39,803 (3.3%) of whom had at least one major birth defect.

Exposure

Offspring were considered exposed if their father had filled at least one prescription in the relevant drug category during spermatogenesis (the three months prior to conception).

Primary and secondary outcome measures

Primary outcome was the diagnosis, in the first year of life, of at least one major birth defect as categorized in the Eurocat guidelines. Secondary outcome was the diagnosis, in the first year of life, of at least one major birth defect in any of the Eurocat subcategories. Adjusted odds ratios (AORs) were calculated, along with their 95% confidence intervals (95% CIs), adjusted for birth year, maternal education, smoking status and age, and paternal education, disposable income and age.

Results

No significant association was found between birth defects and the analyzed drugs. For the largest group, anti-depressants (17,827 exposed births), 3.5% (617) had a birth defect (AOR 0.97 (0.90 to 1.06)). With over 4,000 exposed births for each of the main drug categories, the study was well powered to find moderately elevated birth defect frequencies in exposure groups (minimum detectable odds ratio 1.3 or less). Assuming 50% therapy adherence, the study remained well powered for the largest groups (SSRIs and antidepressants in general).

Conclusions

Antipsychotics, anxiolytics, hypnotics and sedatives, antidepressants, SSRIs, and benzodiazepine-derived anxiolytics are generally safe with regard to birth defects. Further studies are necessary to investigate whether these drugs lead to higher rates of stillbirths, miscarriage, or impaired fertility.

Article summary

- Registry-based cohort study on the effect of paternal prescriptions of some nervous system drugs on birth defects in offspring
- High-quality registry data gives full coverage of population
- Highly powered study for most investigated drugs
- Unable to assess therapy adherence, actual drug intake
- Unable to assess fertility effects of drugs

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Potential competing interests

The authors declare no competing interests.

Introduction

Certain neurological drugs have been associated with adverse changes in semen quality. Beyond common reproductive outcomes like sperm motility, selective serotonin re-uptake inhibitors (SSRIs) have been associated with increased frequencies of DNA fragmentation and abnormal sperm morphology(1-4). Anxiolytics, in particular benzodiazepines, have been associated with chromosomal abnormalities in sperm(5, 6). Of concern, many of these drugs are commonly prescribed to prospective fathers with increasing use over time(7). In Denmark, the proportion of births where the father had been prescribed neurological drugs in the six months preceding conception more than doubled between 1997 and 2017, from approximately 4% to almost 9%. Importantly, prescriptions of antidepressants, mostly SSRIs, increased threefold, to 2.5%(7).

It is known that paternal factors are associated with birth outcomes(8, 9). Given the association of sperm DNA damage in certain neurological drugs, the safety of neurological drugs regarding offspring health needs to be evaluated. In particular, it is unknown whether paternal use of these drugs during spermatogenesis is associated with the risk of birth defects.

To fill this lacuna, we performed a cohort study on all singleton live births in Denmark 1997-2016 (1,201,119 births), linking national registries: the birth registry, the prescription registry and the patient registry. We then assessed for any association between specific neurological drugs prescribed to the father to be in the

three months just prior to conception (one spermatogenic cycle) and birth defects diagnosed in the first year of life.

Methods

Data and inclusion criteria

We obtained the Danish Medical Birth Registry (MFR, (10)) 1997-2016, which contains all births in Denmark from 20 weeks of gestation onwards. In addition to characteristics of the newborn and pregnancy, such as gestation age and Apgar score, this registry contains the CPR number(11), a unique identifier that all Danish citizens and residents have been given since 1968, for newborn, mother and father (if known). We used this CPR number to link registries, meaning that entries with unusable or missing CPR number of either parent or offspring were deleted. Stillbirths were also deleted due to dissimilar ascertainment of birth defects (see below). Approximate conception date is contained in the MFR as birth date minus estimated gestation age.

We linked this registry to the Danish National Prescription Registry (LMDB, (12)), which we obtained for 1995 through mid 2018. This registry gives complete coverage of all prescriptions filled in Denmark by persons with a CPR number. In Denmark, over-the-counter drug prescriptions are severely limited; common pain medication like paracetamol is not freely available in large packages. From this registry we created indicator variables for exposure (see below). We also used this registry to identify those births where the mother had taken any of the investigated drugs up to giving birth (see further Statistical Analyses below).

We further linked with the Danish National Patient Registry (LPR, (13)) 1995 through mid 2018, which contains diagnoses for all in- and out-patient contacts, albeit not for diagnoses in the family doctor setting. This registry includes birth defects, which we classified according to the Eurocat guidelines(14), allowing one year of follow-up upon birth. Birth defects which Eurocat classified as minor were excluded.

Other variables from Statistics Denmark were merged in, such as highest achieved education and paternal disposable income (by year). We further linked with the Population Registry to give birth date and sex of the parents. Births with fathers of unknown or female sex were removed, as were births to mothers of male sex.

Outcome

The primary outcome was the diagnosis of at least one major birth defect in the first year after birth (binary variable), categorized as per the EUROCAT guidelines(14). The secondary outcome was being diagnosed with at least one major birth defect (binary variable) in any of the EUROCAT subcategories.

Exposure

As one spermatogenic cycle takes approximately 3 months(15), we considered offspring whose father filled a prescription in the relevant category during the three months preconception as exposed. We examined the following medication categories: antipsychotics (N05A), amongst which diazepines, oxazepines, thiazepines and oxepines (N05AH); anxiolytics (N05B), amongst which benzodiazepine-derived anxiolytics (N05BA); hypnotics and sedatives (N05C), amongst which benzodiazepines (N05CD); and antidepressants (ATC code N06A), amongst which SSRIs (N06AB).

Missing data

As approximately 15% of the merged records had at least one entry missing, in particular maternal smoking status, we imputed 10 datasets in a procedure described in detail in the Statistical Appendix under the assumption of missingness at random. Reported results are estimates and standard errors pooled under Rubin's rule. Imputation and pooling was handled with the R package *mice(16)* (version 3.8.0).

Statistical analyses

We employed flexible logistic regressions using generalized additive models (GAMs) with R package *mgcv* (17) version 1.8-33, which allow nonlinear smooth associations between the exposure variable and the birth

defect risk. Categorical variables were modelled by simple indicator variables for each level. From these models we obtained odds ratios and their 95% confidence intervals for being diagnosed with at least one major birth defect in the first year of life after adjusting for birth year, maternal factors (smoking status during pregnancy, highest achieved education, maternal age), and paternal factors (disposable income, highest achieved education, paternal age). These potential confounders were selected prior to the analysis for their potential relatedness to both the predictor and outcome(18-21) and were not selected based on their significance.

We compared exposed versus unexposed groups for each drug group separately, first for all liveborn singletons. As a sensitivity analysis we then repeating this analysis excluding births where the mother had taken any of the investigated drugs at any time up to birth. We then analyzed the distribution across Eurocat organ subgroups without excluding birth based on maternal drug use.

All data analyses were carried out on the secure server of Statistics Denmark and run in R (22) version 3.6.3.

Minimum detectable risk and odds ratio calculations

We calculated minimum detectable odds ratios at 80% and 90% power using the software *PS Power and Sample Size,* version 3.1.6(23), both for the actual exposure numbers and under the assumption that 50% of the fathers actually took their prescriptions. Because some drugs suggested a fairly strongly selected group (see Results), we conservatively assumed a 1:10 exposed:unexposed ratio for these calculations (the larger groups tended to be less selected, see results).

Patient and Public Involvement statement

Patients or the public were not involved in the planning, executing and communication of this study.

Results

The cohort

Among the 1,201,119 births available for analysis, i.e. liveborn singletons, 17,827 offspring were exposed to any antidepressants, including 11,902 to SSRIs; 4,301 to antipsychotics, including 1,633 to diazepines, oxazepines, thiazepines and oxepines; 4,918 to anxiolytics (primarily benzodiazepines, n=4,742); and 5,797 to hypnotics and sedatives, of which 1,153 to benzodiazepines (Tables 1 and 2). Grouping (benzo)diazepines resulted in 7,349 exposed births. Exclusion of births where the mother had taken any of the drugs investigated prior to delivery reduced the exposure numbers (by approximately 1/3), representative of the correlation between both parents for these drugs (Table 2).

Fathers who were prescribed any neurological medication before conception were older, as where their partners (Table 1). Differences in education, income, maternal smoking, and parity were also noted. Preterm percentages were slightly higher in the drug exposed groups (>6%) versus the non-exposed group (5%). The sex ratio was similar for all exposure groups relative to the non-exposed group.

Missing data and multiple imputation is unlikely to have influenced these results as the regression results with or without multiple imputation showed only very modest effects for potential confounders, mostly maternal education with an adjusted odds ratio around 1.1 for low education.

Birth defects analysis

Birth defects in children of fathers exposed to neurological drugs before conception were generally similar to those in the unexposed population (3.3-3.9% exposed vs 3.3% unexposed, Table 1). After multivariable adjustment, all 95% confidence intervals crossed unity (Table 2). For antidepressants and SSRIs, the ORs were 0.97 (0.90 to 1.06) and 0.94 (0.85 to 1.04), respectively (all liveborn singletons), and 0.96 (0.86 to 1.06) and 0.97 (0.85 to 1.10) after exclusion. There was a moderate but not statistically significant tendency towards

higher birth defect risk among children whose fathers were prescribed diazepines, oxazepines, thiazepines and oxepines (N05AH), which showed an adjusted odds ratio (AOR) of 1.23 (95% CI: 0.97 to 1.55) for all liveborn singletons, and 1.14 (0.81 to 1.59) after exclusion of mothers ever prescribed any drug in the groups investigated here. In this group, birth defects appeared especially elevated in the urinary tract (Table 3).

Power and detactable odds

At 80% or 90% power, the minimum detectable odds ratio was between 1.1 and 1.3 for the larger groups, but approximately 1.5 for the smaller groups (N05AH and N05CD, Table 4). Assuming a therapy adherence of 50%, minimum detectable odds ratios were approximately 1.3 for antidepressants or SSRIs, approximately 1.5 for antipsychotics, anxiolytics, hypnotics and sedatives, as well as for benzodiazepine-derived anxiolytics. For benzodiazepines as hypnotics and sedatives (N05CD), minimum detectable odds ratios could be as high as 2.1 (Table 4).

Discussion

Summary

The current study found no association between common neurological drugs prescribed to the father in the three months pre-conception and birth defects. The only medication group that suggested a possible effect was diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH), which showed a moderately elevated, but not statistically significant odds ratio of 1.23 (0.97 to 1.55)) for all liveborn singletons. The point estimate reduced to 1.14 when excluding births where mothers had been prescribed any of the investigated drugs at any time up to delivery. The number of births with paternal exposure to each of the drugs was generally large enough to detect a clinically significant elevation in risk, for the larger groups even when assuming that only half the fathers took the medication that they had been prescribed. In general, paternal use of these drugs before conception seems safe with regard to birth defects.

Strengths and limitations

The design of a nationwide, registry-based cohort study allowed the inclusion of large numbers of fathers who were prescribed the investigated drugs just before conception, and to ascertain whether their offspring had birth defects. Although our measure of paternal exposure was indirect – filling a prescription does not equate with taking the drugs – the study had power to overcome exposure misclassification.

We did not have information on paternal lifestyle factors, such as exercise or smoking, and there may have been maternal factors (e.g. genetic predisposition, lifestyle factors like exercise) for which we could not control. We saw significant differences in demographics between fathers prescribed drugs and those who were not. However, these factors are unlikely to have biased the results towards the null because that would require paternal drug prescriptions to correlate with protective maternal or paternal factors.

Even using registry data, there remains a possibility that offspring of fathers prescribed neurological drugs are less visible to the healthcare system because of the fathers' psychological or psychiatrical ailments. Nevertheless, Denmark has universal healthcare with scheduled check-ups for newborns, both at birth and in the first year of life.

Interpretation, possible mechanism, comparison with the literature

Although sperm DNA damage suggests a risk to offspring, this risk may not materialize if sperm with damaged DNA fail to fertilize an egg cell, if the oocyte corrects any DNA damage, if the conceptus fails to develop into a viable fetus, or if the fetus is aborted. Hence, sperm damage could lead to subfertility or infertility, but not birth defects. As the Danish Medical Birth Registry covers only pregnancies from week 20 onwards, further studies are necessary to explore this hypothesis.

Literature on paternal effects on offspring is limited. Certainly, it is reasonable to expect that the nine months a fetus spends developing *in utero* gives more scope for teratogenic effects from maternal exposure than preconception spermatogenic paternal contribution. Yet there is increasing evidence that sperm contributes

more than DNA alone(24), and the early stages of pregnancy are also the most vulnerable stages with regard to birth defects.

The observation of a tendency towards increased risk in N05AH may be due to the disease rather than drug, although antipsychotics as a whole, including N05AH, only very mildly tended towards an increased odds ratio, while neither birth defects of the nervous system nor chromosomal birth defects were elevated in this group. The attenuation of the point estimate seen when excluding births where mothers had been on any of these drugs may indicate confounding by maternal effects.

Conclusion

No association was identified between paternal prescribed neurological drugs (i.e antipsychotics, anxiolytics, hypnotics and sedatives, antidepressants, and SSRIs, benzodiazepine-derived anxiolytics) three months before conception and birth defects in the offspring. As such, men can be counseled that these medications likely do not increase the risk of birth defects. Further studies are necessary to investigate whether these drugs lead to higher rates of stillbirths, early abortions, or failure to fertilize.

Author statement

MLE, RL-J, NES, YL and TKJ designed the study. MJW, YL and LT handled data and statistical analysis. MJW wrote the first draft. All authors interpreted the results, revised the manuscript and approved the final version.

Data statement

Data from Statistics Denmark cannot be made publicly available but can be applied for through the usual ways at DST.dk

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Table 1. Cohort characteristics by drug use. Group "None of the specified drugs" refers to no drugs that occur in the other columns. Other columns may overlap. In particular, benzo(diazepines) are subgroups of antipsychotics (N05A), anxiolytics (N05B), and hypnotics and sedatives (N05C). Income father refers to disposable income in thousands of Danish crowns per year.

	None of the specified drugs (1,173,447)	Antipsychotics (4,301)	Anxiolytics (4,918)	Hypnotics and sedatives (5,797)	Antidepressants (17,827)	(benzo) Diazepines (7,075)
Age father, years (mean (Q1 -Q3))	33.0 (29.2 – 36.4)	34.1 (29.0 – 38.7)	36.0 (30.9 – 40.4)	36.4 (31.5 – 40.2)	34.6 (30.2 – 38.4)	35.7 (30.6 – 40.2)
Age mother, years (mean (Q1 – Q3))	30.4 (27.2 – 33.7)	30.0 (25.8 – 34.0)	31.0 (27.2 – 34.8)	31.3 (27.5 – 35.2)	31.0 (27.4 – 34.6)	30.8 (26.8 – 34.7)
Gestation age, days (mean (Q1 – Q3))	279 (273 – 287)	277 (272 – 286)	277 (272 – 286)	277 (272 – 286)	278 (272 – 286)	277 (272 – 286)
Pre-term (% (N))	5.0% (57,395)	6.7% (288)	6.5% (319)	6.2% (357)	5.8% (1,027)	6.6% (464)
Birth weight, kg (mean (Q1 – Q3))	3.5 (3.2 – 3.9)	3.4 (3.1 – 3.8)	3.4 (3.1 – 3.8)	3.5 (3.1 – 3.8)	3.5 (3.2 – 3.9)	3.4 (3.1 – 3.8)
Birth length, cm (mean (Q1 – Q3))	52 (50 – 54)	51 (50 – 53)	52 (50 – 53)	52 (50 – 53)	52 (50 – 53)	51 (50 – 53)
Apgar score <8 (% (N))	1.3% (15,238)	1.7% (73)	1.6% (78)	1.3% (74)	1.6% (288)	1.5% (108)
Low education father (% (N))	18.6% (218,199)	44.8% (1,928)	38.8% (1,908)	32.3% (1,872)	28.6% (5,101)	40.9% (2,884)
High education father (% (N))	11.9% (139,466)	5.6% (241)	7.3% (358)	10.6% (614)	9.4% (1,678)	6.9% (483)
Low education mother (% (N))	17.8% (208,772)	40.4% (1,737)	35.2% (1,730)	31.0% (1,799)	24.8% (4,423)	37.2% (2,625)
High education mother (% (N))	10.8% (126,861)	5.2% (225)	6.2% (306)	8.8% (507)	9.2% (1,637)	5.9% (413)
Mother quit smoking (% (N))	2.3% (26,752)	4.0% (171)	3.1% (151)	2.5% (146)	3.2% (569)	3.3% (229)
Mother smoked (% (N))	11.8% (138,060)	25.0% (1,075)	26% (1,281)	20.1% (1,164)	17.8% (3,176)	25.9% (1,831)
Income father (mean (Q1 - Q3))	205 (137 – 247)	147 (104 – 172)	158 (101 – 191)	183 (106 – 218)	181 (119 – 224)	153 (102 – 186)
Parity 0 (% (N))	45.6% (535,189)	45.7 (1,967)	41.3% (2,030)	42.6% (2,467)	41.6% (7,414)	42.9% (3,042)
Parity 1 (% (N))	37.1% (434,955)	30.5% (1,313)	33.4% (1,643)	32.7% (1,898)	36.2% (6,450)	31.9% (2,251)
Parity 2 (% (N))	13.3% (155,725)	15.4% (662)	15.8% (775)	15.5% (899)	15.3% (2,727)	15.8% (1,112)
Parity 3 or more (% (N))	4.1% (47,578)	8.3% (359)	9.6% (470)	9.2% (533)	6.9% (1,236)	9.5% (670)
Boys (% (N))	51.3% (602,352)	50.8% (2,185)	51.7% (2,544)	51.4% (2,979)	51.6% (9,204)	51.8% (3,657)
Major birth defect (% (N))	3.3% (38,839)	3.9% (167)	3.5% (173)	3.3% (190)	3.5% (617)	3.6% (254)

Table 2. Specific neurological drugs associated with sperm damage and their adjusted odds ratios (AORs) for having at least one major birth defect. All liveborn singletons, and excluding births where mothers used any drug in groups N03 through N07 at any time up to birth. Odds ratios and p-values adjusted for birth year, paternal age, income and education, and maternal age, smoking status and education. Separate models per drug. Exposure taken as binary: having at least one prescription in the three month preconception timeframe. Is it pharmacologically justified to add up diazepines and benzodiazepines?

Drug class	N	Birth defects	AOR	95% CI
Antipsychotics (N05A)	4,301	3.9% (167)	1.08	0.92 to 1.26
-after exclusion	2,590	3.3% (85)	0.96	0.77 to 1.20
Anxiolytics (N05B)	4,918	3.5% (173)	1.07	0.92 to 1.25
-after exclusion	3,153	3.2% (102)	1.04	0.85 to 1.27
Hypnotics and sedatives (N05C)	5,797	3.3% (190)	0.97	0.83 to 1.13
-after exclusion	3,706	3.2% (119)	1.00	0.83 to 1.21
Diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH)	1,633	4.7% (76)	1.23	0.97 to 1.55
-after exclusion	902	4.1% (37)	1.14	0.81 to 1.59
Benzodiazepine-derived anxiolytics (N05BA)	4,742	3.5% (166)	1.07	0.91 to 1.25
-after exclusion	3,047	3.2% (97)	1.02	0.83 to 1.26
Benzodiazepines as hypnotics and sedatives (N05CD)	1,153	3.1% (36)	0.97	0.69 to 1.36
-after exclusion	736	2.9% (21)	0.93	0.60 to 1.45
(Benzo)diazepines grouped (N05AH, N05BA or N05CD)	7,349	3.6% (254)	1.06	0.94 to 1.21
-after exclusion	4,428	3.3% (147)	1.04	0.88 to 1.23
Antidepressants (N06A)	17,827	3.5% (617)	0.97	0.90 to 1.06
-after exclusion	11,487	3.2% (372)	0.96	0.86 to 1.06
SSRIs (N06AB)	11,902	3.3% (397)	0.94	0.85 to 1.04
-after exclusion	7,751	3.3% (254)	0.97	0.85 to 1.10

Table 3. Eurocat subgroups (binary: ≥1) by drug class, all liveborn singletons. Notice that offspring may appear in more than one category. Publication of numbers smaller than 5 not permitted.

Birth defect category	All (1,173,447)	Antipsychotics (4,301)	Anxiolytics (4,918)	Hypnotics and sedatives (5,797)	Antidepressants (17,827)	(Benzo)diazepines (7,349)	N05AH (1,633)
Digestive	0.21% (2,556)	0.28% (12)	0.12% (6)	0.19% (11)	0.19% (33)	0.16% (11)	0.37% (6)
Urinary	0.26% (3,139)	0.37% (16)	0.33% (16)	0.38% (22)	0.29% (51)	0.40% (28)	0.73% (12)
Heart	0.70% (8,397)	0.77% (33)	0.79% (39)	0.78% (45)	0.70% (125)	0.79% (56)	0.73% (12)
Chromosomal	0.11% (1,339)	≤0.12% (≤5)	≤0.10% (≤5)	≤0.09% (≤5)	0.11% (20)	≤0.07% (≤5)	≤0.1% (≤5)
Limb	0.93% (11,132)	0.93% (40)	0.96% (47)	0.67% (39)	0.94% (167)	0.91% (64)	1.16% (19)
Nervous	0.11% (1,364)	0.19% (8)	0.14% (7)	0.16% (9)	0.08% (15)	0.13% (9)	≤0.1% (≤5)
Eye	0.12% (1,445)	≤0.12% (≤5)	0.14% (7)	≤0.09% (≤5)	0.12% (22)	0.11% (8)	≤0.1% (≤5)
Genital	0.25% (2,945)	0.21% (9)	0.22% (11)	0.24% (14)	0.30% (54)	0.24% (17)	≤0.1% (≤5)
Oro-facial clefts	0.15% (1,761)	0.19% (8)	≤0.10% (≤5)	0.16% (9)	0.13% (23)	0.11% (8)	≤0.1% (≤5)
Other	0.64% (7,655)	1.05% (45)	0.92% (45)	0.79% (46)	0.80% (142)	0.91% (64)	1.29% (21)

Table 4. Minimum risks detectable as abberant. Based on a univariate binomial model with population risk of 3.3% assuming a 1:10 exposed:unexposed ratio. The two rightmost columns assume a 50-50 mix between the population risk of 3.3% and the risk among the exposed.

Drug class	N	Minimum detectable odds ratio			
		Assuming 100% therapy adherence		Assuming 50% therapy adherence	
		80% power	90% power	80% power	90% power
Antipsychotics (N05A)	4301	1.25	1.32	1.51	1.64
Anxiolytics (N05B)	4918	1.25	1.28	1.51	1.57
Hypnotics and sedatives (N05C)	5797	1.22	1.25	1.45	1.51
Diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH)	1633	1.45	1.54	1.90	2.10
Benzodiazepine-derived anxiolytics (N05BA)	4742	1.25	1.28	1.51	1.57
Benzodiazepines as hypnotics and sedatives (N05CD)	1153	1.54	1.64	2.10	2.31
(Benzo)diazepines grouped (N05AH, N05BA or N05CD)	7349	1.19	1.22	1.38	1.45
Antidepressants (N06A)	17827	1.13	1.16	1.25	1.32
SSRIs (N06AB)	11902	1.16	1.19	1.32	1.38

Statistical appendix to: Nervous system drugs taken by future fathers and birth defects in offspring: a registry-based cohort study

Statistical appendix

M.J. Wensink, Y. Lu, L. Tian

Introduction and summary

Since some observations were partially missing, either because they were treated as such (see below), or, mostly, because they were missing in the original dataset, we planned to impute those observations before running generalized additive models on the imputed datasets, and combine the results through Rubin's rule. At the moment of imputation, we had variables such as gestational age, smoking status of the mother, and education of both parents, as well as a large number of binary variables for drug exposures. We had 973 drugs which at least one father was prescribed during the three months preconception, 945 drugs that at least one mother was prescribed during the first trimester of pregnancy, and 885 drugs that at least one mother was prescribed during the rest of pregnancy. We also had various indicator covariates for maternal and paternal conditions, as well as 14 subgroups of birth defects (for example birth defects of the heart, etc.). Because imputation on all these covariates was impractical giving computational limitations, we set up the following approach.

1. We ran a lasso algorithm on the complete cases, from which we selected an appropriate set of variables to impute from for each of the variables that had missing data.
2. We ran multiple imputation by chained equations, imputing each of the missing value of a variable based on variables selected by the lasso algorithm for the variable of interest.
3. We ran logistic regressions with the logit link function through generalized additive models based on entire datasets after imputing all missing values and pooled the results through Rubin's rule.

The lasso algorithm used linear relationships only and no interactions were considered. For multiple imputation and logistic regressions, we used approaches that allowed a maximum of flexibility with regard to departures from linearity. In particular, for imputation we used predictive mean matching for numeric variables and simple indicator variables for each group of categorical variables (without further assumptions such as the proportional odds assumption), while for the logistic regressions we used scatterplot smoothers (thin plate splines with four knots spaced uniformly, i.e. the default setting of the statistical software – changing to cubic splines did not change the results) for numeric variables and again simple indicator variables for each group of categorical variables. Details are given below.

Data preparation and missingness

This analysis concerns liveborn singletons only. Birth lengths below 21 cm (often 0 cm or 10 cm, 8412 births) or above 69 cm (538 births) were treated as missing. Birth weights below 366 g (often 0 g or 100 g, 2091 births) and above 6583 g (63 births) (+/- 5 standard deviations) were treated as missing. At least master-level education was relabeled as high education. Education ranging from upper secondary to bachelor level was

relabeled as middle education. Primary and lower secondary education were relabeled as low education. This relabeling was based on divergent trends of preconception drug use in this data set published elsewhere (reference 3 of the main manuscript). Education not elsewhere classified was treated as missing (1883 and 3669 births for father and mother, respectively). Maternal smoking was relabeled as no smokers, current smokers, and quit during pregnancy (thus collapsing the various moments of quitting during pregnancy).

After applying exclusion criteria, i.e. for observations used in the final analysis, we had the following numbers of missing data:

Variable	**Number missing net of exclusion criteria**
Apgar score	8,531 (0.8%)
Birth length	13,001 (1.2%)
Birth weight	5,594 (0.5%)
Hospital days upon birth	6,015 (0.5%)
Disposable income father	4,818 (0.4%)
Education father	41,895 (3.8%)
Education mother	37,314 (3.4%)
Smoking status mother	92,448 (8.4%)
At least one variable missing	168,871 (15.3%)

Notice that while Apgar score, birth weight and length, and number of hospital days were not involved in the main analysis, they had to be imputed because other imputations might rely on them. For the same reason we initially imputed the 27,080 missing gestation ages.

Lasso

For the lasso algorithm, all numeric variables were standardized by subtracting the mean and dividing by twice their standard deviation. Binary variables were not standardized. To allow for convergence in reasonable time, we first selected even years only, after which we sampled without replacement 1 in every 5 observation, giving approximately 10% of the original data or some 100 thousand (100K) observations. On this reduced dataset we then ran the lasso cross validation algorithm of R package *glmnet* (version 4.0-2), i.e. cv.glmnet() with alpha=1. From the cross validation results (representative example in Figure 1), we selected an appropriate number of variables from which to impute.

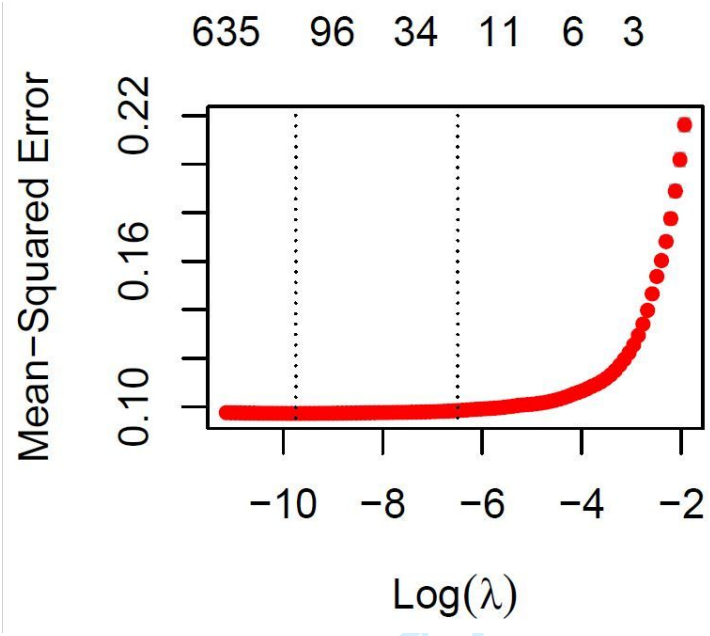

Figure 1. An example of a lasso result, in this case of gestation age on a sample of 100K observations. On the x-axes the number of non-zero covariates (top) along with the log of the penalty parameter λ (bottom). The loss (mean squared error) is given as the y-axis. Observe that the null model (0 covariates) corresponds to imputing the mean, giving a MSE (≈variance) of 0.25 as a result of our standardization procedure. After log(λ) reaches -6, diminishing returns lead the addition of further covariates to reduce the mean squared error only marginally, whereas the number of variables with non-zero coefficients grows swiftly. In this case we selected a model with 75 variables, striking the middle between sparsity and accuracy (see main text of this Appendix).

In selecting the set of variables to impute from, we considered that we had the following reasons to be generous, i.e., likely to choose a high number of variables:

1. A better, fuller model gives more accurate imputations and so improves the precision of estimates.
2. The relationships in the complete cases may differ somewhat from the relationships in the whole population (if we knew all missing values). Selecting a generous model gives a chance for these relationships to be picked up in the imputation procedure.
3. There would have been some sampling variability in selecting 100K observations from the dataset, in which the relationships may differ somewhat from the remaining (complete cases) dataset. Selecting a generous model gives a chance for this relationship to be picked up in the imputation procedure.
4. Overfitting was not our first concern, since we wished to maximally capture the variability in the data and our sample size is large relative to the number of variables.
5. We had particular reason to be generous for those variables with a high percentage of observations missing (smoking status in particular), so that *ceteris paribus* gains from accurate imputations would be larger (although variability in variables used in those imputations may also propagate).
6. Selecting a small model may lead imputations to depend on variables that are missing at the same time, which little opportunity to seize on other information in the data.

We also had the following reasons to be conservative, i.e. choose a low number of variables:

1. A small model runs faster, which was the aim of the lasso screening step. Multiple imputations based on the entire dataset is too slow and unnecessary.
2. Since there is variability in sampling the subset on which to run lasso, the variables near the minimum loss (the left vertical dashed line in Figure 1) may not be relevant for the rest of the data.

3. Some of the non-zero coefficients in the selected lasso model may not be at their full, unpenalized values. Removing the restriction of penalization may increase the predictive power of the model in the multiple imputation setting without need for additional covariates in the imputation model.

In practice we ended up choosing a model halfway between lambda for the minimum loss (lambda.min) and lambda at one standard error of the minimum loss (lambda.1se). Up to 50 covariates were added to the latter model depending on the location of lambda.min, the amount of missing data, a visual inspection of the plateau, and any pre-existing knowledge on the status of a variable as a confounder, always staying well away from lambda.min. The exceptions to this procedure were the education factor variables, which did not converge on 100K observations. For these variables we divided up the 100K variables in 4 datasets (of 25K variables each), ran the lasso algorithm on each of these, selected the lambda.min model for each, and took the intersection of the four sets of covariates. Hence, the first selection was generous (large number of variables selected), but taking the intersection of the four sets is conservative (small number of variables selected). For education, this procedure gave 59 variables for the father and 105 for the mother. Smoking status of the mother was imputed from 146 variables due to high missingness. The other variables were imputed from much smaller models (11-16 covariates). Thus, we used large models for variables with a relatively large amount of missing data, or that were difficult to predict.

Multiple imputation

Multiple imputation was done using chained equations (Gibbs sampler) under the assumption of missingness at random, implemented in R package *mice* (version 3.8.0) with a custom made predictor matrix set up from the models found through the lasso procedure outlined above. We created 10 imputed datasets using polytomous regression without further assumptions for categorical variables and predictive mean matching for numerical variables. The number of imputed datasets was lower than the 15% suggested by the "one dataset for each percent of missing data" rule, justified because most variables had only low percentages of missing data, and were used only indirectly. Because the default number of 5 iterations suggested that convergence was perhaps not fully achieved for some variables, we ran 10 iterations. Convergence was achieved after 7 iterations.

Logistics regressions (generalized additive model)

We ran logistic regression fully adjusted for birth year, paternal characteristics, and maternal characteristics, as implemented in R package *mgcv* (version 1.8-33). For example,

```
model<-gam(birth defect ~ drug name + s(birth year) +
                education father + s(income father) + s(age father) +
                education mother + smoking status mother + s(age mother),
                data = data,
                subset = liveborn singletons after exclusion criteria,
                family = binomial()
)
```

The scatterplot smoothers used most degrees of freedom for birth year and age mother, and least for income and age father.

Such models were run in functions that ran them for each of the datasets, pooled the estimates, and summarized the results, as implemented in R package *mice*:

estimates <- with(data = data, gam as above *omitting the data statement*)

pooled estimates <- pool(estimates)

model results <- summary(pooled estimates)

STROBE Statement—Checklist of items that should be included in reports of ***cohort studies***
Please find the places in the manuscript of each item indicated in red.

	Item No	Recommendation
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract This is done both in the title (page 1) and the abstract (page 2).
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found Done (abstract, page 2).
Introduction		
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported Done in the first two paragraphs of the introduction (page 4).
Objectives	3	State specific objectives, including any prespecified hypotheses Third (and last) paragraph of introduction (page 4).
Methods		
Study design	4	Present key elements of study design early in the paper The study design is already alluded to at the beginning of the third paragraph of introduction (page 4).
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection Setting, locations and relevant dates are given in the first paragraph of the methods section, bottom of page 4, top of page 5. Exposure is defined in the subsection with that name, bottom of page 5, top of page 6. Follow-up is given in the subsection called "outcome", below the middle of page 5. Data collection not relevant as we used registry data.
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up Elegibility criteria, sources, and methods of participant selection are all given in the "data and inclusion criteria" subsection of methods, bottom of page 4, upper half of page 5. Methods of follow-up (in our case: in the registry) is given in the subsection called "outcome", below the middle of page 5.
		(*b*) For matched studies, give matching criteria and number of exposed and unexposed Not applicable (not matched)
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable Outcomes and exposures are addressed in the respective subsections of the methods section alluded to above. Potential confounders are discussed in the first paragraph of the subsection called "Statistical analyses", lines 126-132. Effect modifiers were not analyzed.
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group We have described for each source, which variables that source yielded ("Data and inclusion criteria", pages 4-5).
Bias	9	Describe any efforts to address potential sources of bias As these are registry data, bias is presumably limited, although visibility to the healthcare system may be an issue. This is mentioned in the discussion, "strengths and

		limitations", page 9.
Study size	10	Explain how the study size was arrived at See first paragraph of results section, "the cohort", page 7.
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why First paragraph of "Statistical analyses", page 6. No groupings were made.
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding First paragraph of "Statistical analyses", page 6. Details on GAMs in Statistical Appendix.
		(*b*) Describe any methods used to examine subgroups and interactions Also "Statistical analyses", page 6, second paragraph (lines 133-136).
		(*c*) Explain how missing data were addressed Please see subsection "missing data" on page 6, as well as the detailed Statistical Appendix.
		(*d*) If applicable, explain how loss to follow-up was addressed Not applicable.
		(*e*) Describe any sensitivity analyses Page 6, lines 134-135.
Results		
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed See first paragraph of results section, "the cohort", page 7.
		(b) Give reasons for non-participation at each stage Not applicable.
		(c) Consider use of a flow diagram We have considered this, but the cohort is relatively straightforward.
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders Table 1 is dedicated to this, discussed in the second paragraph of the first section of the results (page 7).
		(b) Indicate number of participants with missing data for each variable of interest This is summarized in the Statistical Appendix.
		(c) Summarise follow-up time (eg, average and total amount) All offspring were followed-up for one year (in the registry) as stated in the "outcome" subsection of methods.
Outcome data	15*	Report numbers of outcome events or summary measures over time All tables give the absolute numbers the analysis is based on.
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included Crude rates are given in Table 1 (last row); adjusted odds ratios (along with crude rates) are given in Table 2. Confounders as specified above.
		(*b*) Report category boundaries when continuous variables were categorized Not applicable.
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period Not relevant because we did not find an elevated risk.
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and

		sensitivity analyses Table 2 shows how exclusion by maternal criteria changes the results (or rather, how it does not).
Discussion		
Key results	18	Summarise key results with reference to study objectives Discussion, first paragraph, bottom of page 8, top of page 9.
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias Discussion section "strengths and limitations" (page 9) is dedicated to this.
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence Discussion section "Interpretation, possible mechanism, and comparison with literature" (pages 9-10) is dedicated to this.
Generalisability	21	Discuss the generalisability (external validity) of the study results See discussion, page 9, first paragraph of "Interpretation, possible mechanism, and comparison with literature".
Other information		
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based Page 3, "funding".

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at http://www.strobe-statement.org.

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Nervous system drugs taken by future fathers and birth defects in offspring: a prospective registry-based cohort study

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Nervous system drugs taken by future fathers and birth defects in offspring: a prospective registry-based cohort study

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Keywords

Birth defects, congenital anomalies, congenital malformations, paternal effects, drug safety

Ethical approval

This article uses existing registry data (from Denmark), which are exempt from IRB review given that the data are deidentified.

Word count

Abstract: 293 words
Main text: 2,661 words

Abstract

Objectives

To evaluate the association of paternal intake of antipsychotics, anxiolytics, hypnotics and sedatives, antidepressants, SSRIs, and (benzo)diazepines during the development of fertilizing sperm with birth defects in offspring.

Design

Prospective registry based cohort study

Setting

Total Danish birth cohort 1997-2016 using Danish national registries

Participants

All 1,201,119 Danish liveborn singletons born 1997-2016 were eligible, 39,803 (3.3%) of whom had at least one major birth defect.

Exposure

Offspring were considered exposed if their father had filled at least one prescription in the relevant drug category during development of fertilizing sperm (the three months prior to conception).

Primary and secondary outcome measures

Primary outcome was the diagnosis, in the first year of life, of at least one major birth defect as categorized in the Eurocat guidelines. Secondary outcome was the diagnosis, in the first year of life, of at least one major birth defect in any of the Eurocat subcategories. Adjusted odds ratios (AORs) were calculated, along with their 95% confidence intervals (95% CIs), adjusted for year, education, smoking status and age of the mother, and education, disposable income and age of the father.

Results

This study found weak or null associations between birth defects and selected drugs. Specifically, anti-depressants (17,827 exposed births), gave 3.5% birth defects (AOR 0.97 (0.90 to 1.06)). Diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, 1,633 offspring), gave 4.7% birth defects, AOR 1.23 (0.97 to 1.55), attenuated to 1.14 when excluding by mothers' prescriptions. The study was well powered assuming 100% therapy adherence, while assuming 50% therapy adherence the study remained well powered for the largest groups (SSRIs and antidepressants overall).

Conclusions

Antipsychotics, anxiolytics, hypnotics and sedatives, antidepressants, SSRIs, and benzodiazepine-derived anxiolytics, when taken by the father during development of fertilizing sperm, are generally safe with regard to birth defects.

Article summary

- High-quality registry data gives full coverage of population
- Highly powered study for most investigated drugs
- Unable to assess therapy adherence, actual drug intake
- Unable to assess associations between drugs and fertility

Funding

This study was funded by NIH grant HD096468 (to MLE). The funder had no role in the study design, collection, analysis, and interpretation of the data and in the writing of the report.

Potential competing interests

YL reports grants from Merck, and personal fees from United Health Care, Nektar, and Gilead, outside the submitted work. MLE reports advisorships for Sandstone Diagnostics, Dadi, Hannah, and Underdog which are fertility related companies.

Introduction

Certain neurological drugs have been associated with adverse changes in semen quality. Beyond common reproductive outcomes like sperm motility, selective serotonin re-uptake inhibitors (SSRIs) have been associated with increased frequencies of DNA fragmentation and abnormal sperm morphology(1-4). Anxiolytics, in particular benzodiazepines, have been associated with chromosomal abnormalities in sperm(5, 6). Of concern, many of these drugs are commonly prescribed to prospective fathers with increasing use over time(7). In Denmark, the proportion of births where the father had been prescribed neurological drugs in the six months preceding conception more than doubled between 1997 and 2017, from approximately 4% to almost 9%. Importantly, prescriptions of antidepressants, mostly SSRIs, increased threefold, to 2.5%(7).

It is known that paternal factors are associated with birth outcomes such as preterm birth, low birth weight, and neonatal intensive care unit stays(8, 9). Given the association of sperm DNA damage in certain neurological drugs, the safety of neurological drugs regarding offspring health needs to be evaluated. In particular, it is unknown whether paternal use of these drugs during spermatogenesis is associated with the risk of birth defects.

Hence, we performed a cohort study on all singleton live births in Denmark 1997-2016 (1,201,119 births), linking national registries: the birth registry, the prescription registry and the patient registry. We then assessed for any association between specific neurological drugs prescribed to the father to be in the three months just prior to conception (one spermatogenic cycle) and birth defects diagnosed in the first year of life.

Methods

Data and inclusion criteria

We obtained the Danish Medical Birth Registry (MFR, (10)) 1997-2016, which contains all births in Denmark from 20 weeks of gestation onwards. In addition to characteristics of the newborn and pregnancy, such as gestation age and Apgar score, this registry contains the CPR number(11), a unique identifier that all Danish citizens and residents have been given since 1968, for newborn, mother and father (if known). We used this CPR number to link registries, meaning that entries with unusable or missing CPR number of either parent or offspring were deleted. Stillbirths were also deleted due to dissimilar ascertainment of birth defects (see below). Approximate conception date is contained in the MFR as birth date minus estimated gestational age.

We linked this registry to the Danish National Prescription Registry (LMDB, (12)), which we obtained for 1995 through mid 2018. This registry gives complete coverage of all prescriptions filled in Denmark by persons with a CPR number. In Denmark, over-the-counter drug prescriptions are limited; common pain medication like paracetamol is not freely available in large packages. From this registry we created indicator variables for exposure (see below). We also used this registry to identify those births where the mother had taken any of the investigated drugs up to giving birth (see further Statistical Analyses below).

We further linked with the Danish National Patient Registry (LPR, (13)) 1995 through mid 2018, which contains diagnoses for all in- and out-patient contacts, albeit not for diagnoses in the family doctor setting. This registry includes birth defects, which we classified according to the Eurocat guidelines(14), allowing one year of follow-up upon birth. Birth defects which Eurocat classified as minor were excluded.

We incorporated information from Statistics Denmark, the central authority on Danish statistics. These variables were paternal disposable income, the amount of money that a person or household has available for spending and saving after income taxes and interest expenses have been accounted for, and highest achieved education (both by year). We further linked with the Population Registry to give birth date and sex

of the parents. Births with fathers of unknown or female sex were removed, as were births to mothers of male sex.

Outcome

The primary outcome was the diagnosis of at least one major birth defect in the first year after birth (binary variable), categorized as per the EUROCAT guidelines(14), which provide ICD codes of birth defects that they classify as major. The secondary outcome was being diagnosed with at least one major birth defect (binary variable) in any of the EUROCAT subcategories (by organ or tract).

Exposure

As one spermatogenic cycle takes approximately 3 months(15), we considered offspring whose father filled a prescription in the relevant category during the three months preconception as exposed. We examined the following medication categories: antipsychotics (Anatomical Therapeutic Chemical (ATC) classification code N05A), amongst which diazepines, oxazepines, thiazepines and oxepines (N05AH); anxiolytics (N05B), amongst which benzodiazepine-derived anxiolytics (N05BA); hypnotics and sedatives (N05C), amongst which benzodiazepines (N05CD); and antidepressants (N06A), amongst which SSRIs (N06AB).

Missing data

Approximately 15% of the merged records had at least one entry missing, in particular maternal smoking status (Supplemental Table 1, in Statistical Appendix)We imputed 10 datasets in a procedure described in detail in the Statistical Appendix under the assumption of missingness at random. Reported results are estimates and standard errors pooled under Rubin's rule. Imputation and pooling was handled with the R package *mice(16)* (version 3.8.0).

Statistical analyses

We employed flexible logistic regressions using generalized additive models (GAMs) with R package *mgcv* (17) version 1.8-33, which allow nonlinear smooth associations between the exposure variable and the birth defect risk. Categorical variables were modelled by simple indicator variables for each level. From these models we obtained odds ratios and their 95% confidence intervals for being diagnosed with at least one major birth defect in the first year of life after adjusting for birth year, maternal factors (smoking status during pregnancy, highest achieved education, maternal age), and paternal factors (disposable income, highest achieved education, paternal age). These potential confounders were selected prior to the analysis for their potential relatedness to both the predictor and outcome (18-21) and were not selected based on their significance.

We compared exposed versus unexposed groups for each drug group separately, first for all liveborn singletons. As a sensitivity analysis we then repeated this analysis excluding births where the mother had taken any of the investigated drugs at any time prior to birth. We then compared, by conditional logistic regression, exposed versus unexposed offspring of the same father, adjusting for birth year, maternal age, and nulliparity. We then analyzed the distribution across Eurocat organ subgroups without excluding birth based on maternal drug use.

All data analyses were carried out on the secure server of Statistics Denmark and run in R (22) version 3.6.3.

Minimum detectable risk and odds ratio calculations

We calculated minimum detectable odds ratios at 80% and 90% power using the software *PS Power and Sample Size,* version 3.1.6(23), both for the actual exposure numbers and under the assumption that 50% of the fathers actually took their prescriptions. Because some drugs induced highly selective selected groups (see Results), we conservatively assumed an exposed:unexposed ratio of 1:10 for these calculations (the larger groups tended to be less selective, see results).

Patient and Public Involvement statement

Patients or the public were not involved in the planning, executing and communication of this study.

Results

The cohort

The Birth Register had 1,276,229 records for 1997-2016. After exclusion of records with unusable CPR of the offspring (2,888) or father (1,150), 1,272,750 records could be linked to the Patient Register, the Prescription Register, (socioeconomic) variables held at Statistics Denmark, and the Population Register. Excluding births to fathers with registered unknown or female sex (19,163), mothers of male sex (7) and stillbirths (1,927) left 1,251,653 records for multiple imputation. After imputation, excluding records of non-singleton births (50,534) and records with missing gestation age (27,080) left 1,174,727 offspring. Exclusion of births with mothers who filled a prescription of any of the investigated drugs at any time up to birth left 936,706 offspring.

Among the 1,174,727 births available for the main analysis, i.e. liveborn singletons without missing gestational age, 17,827 offspring were exposed to any antidepressants, including 11,902 to SSRIs; 4,301 to antipsychotics, including 1,633 to diazepines, oxazepines, thiazepines and oxepines; 4,918 to anxiolytics (primarily benzodiazepines, n=4,742); and 5,797 to hypnotics and sedatives, of which 1,153 to benzodiazepines (Tables 1 and 2). Grouping (benzo)diazepines resulted in 7,057 exposed births. Exclusion of births where the mother had taken any of the drugs investigated prior to delivery reduced the exposure numbers (by approximately 1/3), representative of the correlation between both parents for these drugs (Table 2).

Fathers who were prescribed any neurological medication before conception were older, as were their partners (Table 1). Differences in education, income, maternal smoking, and parity were also noted. Preterm

percentages were slightly higher in the drug exposed groups (>6%) versus the non-exposed group (5%). The sex ratio was similar for all exposure groups relative to the non-exposed group.

Multiple imputation results suggested that missing data were unlikely to have influenced the results from the complete case analysis. The regression results with or without multiple imputation showed only very modest associations for potential confounders, mostly maternal education with an adjusted odds ratio just below 1.1 for low education.

Birth defects analysis

Birth defects in children of fathers exposed to neurological drugs before conception were generally similar to those in the unexposed population (3.3-3.9% exposed vs 3.3% unexposed, Table 1). After multivariable adjustment, all 95% confidence intervals included unity (Table 2). For antidepressants and SSRIs, the ORs were 0.97 (0.89 to 1.05) and 0.94 (0.85 to 1.04), respectively (all liveborn singletons), and 0.95 (0.85 to 1.05) and 0.96 (0.85 to 1.09) after exclusion. There was a moderate but not statistically significant tendency towards higher birth defect risk among children whose fathers were prescribed diazepines, oxazepines, thiazepines and oxepines (N05AH), which showed an adjusted odds ratio (AOR) of 1.22 (95% CI: 0.97 to 1.54) for all liveborn singletons, and 1.13 (0.81 to 1.57) after exclusion of births to mothers ever prescribed any drug in the groups investigated here. Results were similar in the siblings analysis (Table 2). In this group, birth defects appeared especially elevated in the urinary tract (0.73% versus 0.26%, $p<0.001$ ($p=0.04$ after Šidàk correction for multiple testing), Table 3).

Power and detectable odds

At 80% or 90% power, the minimum detectable odds ratio was between 1.1 and 1.3 for the larger groups, but approximately 1.5 for the smaller groups (N05AH and N05CD, Table 4). Assuming a therapy adherence of 50%, minimum detectable odds ratios were approximately 1.3 for antidepressants or SSRIs, approximately 1.5 for antipsychotics, anxiolytics, hypnotics and sedatives, as well as for benzodiazepine-derived anxiolytics.

For benzodiazepines as hypnotics and sedatives (N05CD), minimum detectable odds ratios could be as high as 2.1 (Table 4).

Discussion

Summary of findings

The current study found weak or null associations between offspring birth defects and prescriptions of common neurological drugs filled by the father during the three months pre-conception. The only medication group that suggested a possible association was diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH), which showed a moderately elevated, but not statistically significant odds ratio of 1.22 (0.97 to 1.54)) for all liveborn singletons. The point estimate reduced to 1.13 after excluding offspring whose mother had filled a prescription of any of the investigated drugs at any time prior to delivery. For SSRIs, a large group with the strongest prior evidence of associated sperm damage, the adusted odds ratio was 0.94 (0.85 to 1.04) before exclusion, and 0.96 (0.85 to 1.09) after exclusion. Results were similar when comparing exposed to unexposed siblings. The number of births with paternal exposure to each of the drugs was generally large enough to detect a clinically significant elevation in risk, for the larger groups even when assuming that only half the fathers took the medication that they had been prescribed. In general, paternal use of these drugs before conception seems safe with regard to birth defects.

Strengths and limitations

The design of a nationwide, registry-based cohort study allowed the inclusion of large numbers of fathers who were prescribed the investigated drugs just before conception, and to ascertain whether their offspring had birth defects. The registries used are generally complete and of high quality, with (hospital) reimbursement generally depending on reporting and with cross-checks between registries in place. Further information can be found in references 10-13. Although our measure of paternal exposure was indirect – filling a prescription does not equate with taking the drugs – the study had power to overcome exposure

misclassification. Dosage and exact timing of exposure were not considered, which could have biased our results towards the null.

We did not have information on paternal lifestyle factors, such as exercise or smoking, and there may have been maternal factors (e.g. genetic predisposition, lifestyle factors like exercise) for which we could not control. We saw significant differences in demographics between fathers prescribed drugs and those who were not. However, these factors are unlikely to have biased the results towards the null because that would require paternal drug prescriptions to correlate with protective maternal or paternal factors.

Even using registry data, there remains a possibility that offspring of fathers prescribed neurological drugs are less visible to the healthcare system because of the fathers' psychological or psychiatrical ailments. This could result in reduced birth defect ascertainment for these offspring, and hence bias the results towards (or even below) the null. Nevertheless, Denmark has universal healthcare with scheduled check-ups for newborns, both at birth and in the first year of life, and we restricted to birth defects classified by Eurocat as major. Thus, it seems reasonable to suspect that the majority of birth defects would be diagnosed. However, if there was an association between a paternal medication and an earlier reproductive outcome (e.g. fertilization, miscarriage), the effect on birth defects could be interpreted as bias toward the null.

Interpretation, possible mechanism, comparison with the literature

Although sperm DNA damage suggests a risk to offspring, this risk may not materialize if sperm with damaged DNA fail to fertilize an egg cell, if the oocyte corrects any DNA damage, if the conceptus fails to develop into a viable fetus, or if the fetus is aborted. Hence, sperm damage could lead to subfertility or infertility, but not birth defects. As the Danish Medical Birth Registry covers only pregnancies from week 20 onwards, further studies are necessary to explore this hypothesis.

Literature on paternal effects on offspring is limited. Certainly, it is reasonable to expect that the nine months a fetus spends developing *in utero* gives more scope for teratogenic effects from maternal exposure than

preconception spermatogenic paternal contribution. Yet there is increasing evidence that sperm contributes more than DNA alone(24), and the early stages of pregnancy are also the most vulnerable stages with regard to birth defects.

The observation of a tendency towards increased risk in diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH) may be due to the disease rather than drug, although antipsychotics as a whole only very mildly tended towards an increased odds ratio, while neither birth defects of the nervous system nor chromosomal birth defects were elevated in this group. However, a prior study did suggest a possible association between paternal diazepam and perinatal mortality and growth retardation (25). The attenuation of the point estimate seen when excluding births where mothers had been on any of these drugs may indicate confounding by maternal associations. On the other hand, if a significant share of the N05AH-exposed offspring were actually unexposed, because the father may not have taken the filled prescription, 1.23 may be an underestimate of the true association.

Conclusion

The current study found weak or null associations between prescriptions of neurological drugs (i.e antipsychotics, anxiolytics, hypnotics and sedatives, antidepressants, and SSRIs, benzodiazepine-derived anxiolytics) filled by the father during the development of fertilizing sperm (three months before conception) and birth defects in the offspring. Paternal use of diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH) during the development of fertilizing sperm may be associated with mildly elevated birth defect frequencies, although a maternal pathway is not excluded here, and although this observation could be due to chance. As such, men can be counseled that these medications likely do not increase the risk of birth defects. Further studies are necessary to investigate whether these drugs lead to higher rates of stillbirths, early abortions, or failure to fertilize, as well as the group N05AH.

Author statement

MLE, RL-J, NES, YL and TKJ designed the study. MJW, YL and LT handled data and statistical analysis. MJW wrote the first draft. All authors interpreted the results, revised the manuscript and approved the final version.

Data and protocol statement

Data from Statistics Denmark cannot be made publicly available but can be applied for through the usual ways at DST.dk. The grant proposal is summarized here: https://reporter.nih.gov/search/C3FoCZUipkCJsZsijQP4LA/project-details/9585127#details

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Table 1. Cohort characteristics by drug use for all liveborn singletons in Denmark 1996-2016. Group "None of the specified drugs" refers to no drugs that occur in the other columns. Other columns may overlap. In particular, benzo(diazepines) are subgroups of antipsychotics (N05A), anxiolytics (N05B), and hypnotics and sedatives (N05C). Income father refers to disposable income in thousands of Danish crowns per year.

	None of the specified drugs (1,147,005)	Antipsychotics (4,301)	Anxiolytics (4,918)	Hypnotics and sedatives (5,797)	Antidepressants (17,827)	(benzo) Diazepines (7,057)
Age father, years (mean (Q1 - Q3))	33.0 (29.2 - 36.4)	34.1 (29.0 - 38.7)	36.0 (30.9 - 40.4)	36.4 (31.5 - 40.2)	34.6 (30.2 - 38.4)	35.7 (30.6 - 40.2)
Age mother, years (mean (Q1 - Q3))	30.4 (27.2 - 33.7)	30.0 (25.8 - 34.0)	31.0 (27.2 - 34.8)	31.3 (27.5 - 35.1)	31.0 (27.4 - 34.6)	30.8 (26.8 - 34.7)
Gestation age, days (mean (Q1 - Q3))	279 (273 - 287)	277 (272 - 286)	277 (272 - 286)	277 (272 - 286)	278 (272 - 286)	277 (272 - 286)
Pre-term (% (N))	5.0% (57,395)	6.7% (288)	6.5% (319)	6.2% (357)	5.8% (1,027)	6.6% (464)
Birth weight, kg (mean (Q1 - Q3))	3.5 (3.2 - 3.9)	3.4 (3.1 - 3.8)	3.4 (3.1 - 3.8)	3.5 (3.1 - 3.8)	3.5 (3.2 - 3.9)	3.4 (3.1 - 3.8)
Birth length, cm (mean (Q1 - Q3))	52 (50 - 54)	51 (50 - 53)	52 (50 - 53)	52 (50 - 53)	52 (50 - 53)	51 (50 - 53)
Apgar score <8 (% (N))	1.3% (15,001)	1.7% (73)	1.6% (78)	1.3% (74)	1.6% (288)	1.5% (108)
Low education father (% (N))	19.0% (213,009)	44.8% (1,928)	38.8% (1,908)	32.3% (1,872)	28.6% (5,101)	40.9% (2,884)
High education father (% (N))	12.0% (136,825)	5.6% (241)	7.3% (358)	10.6% (614)	9.4% (1,678)	6.9% (483)
Low education mother (% (N))	18.0% (204,933)	40.4% (1,737)	35.2% (1,730)	31.0% (1,799)	24.8% (4,423)	37.2% (2,625)
High education mother (% (N))	11.0% (124,850)	5.2% (225)	6.2% (306)	8.8% (507)	9.2% (1,637)	5.9% (413)
Mother quit smoking (% (N))	2.0% (26,752)	4.0% (171)	3.1% (151)	2.5% (146)	3.2% (569)	3.3% (229)
Mother smoked (% (N))	12.0% (138,007)	25.0% (1,075)	26% (1,281)	20.1% (1,164)	17.8% (3,176)	25.9% (1,831)
Income father (mean (Q1 - Q3))	205 (138 - 248)	147 (104 - 172)	158 (101 - 191)	183 (106 - 218)	181 (119 - 224)	153 (102 - 186)
Parity 0 (% (N))	45.6% (523,304)	45.7 (1,967)	41.3% (2,030)	42.6% (2,467)	41.6% (7,414)	42.9% (3,042)
Parity 1 (% (N))	37.2% (426,557)	30.5% (1,313)	33.4% (1,643)	32.7% (1,898)	36.2% (6,450)	31.9% (2,251)
Parity 2 (% (N))	13.2% (151,369)	15.4% (662)	15.8% (775)	15.5% (899)	15.3% (2,727)	15.8% (1,112)
Parity 3 or more (% (N))	4.0% (45,825)	8.3% (359)	9.6% (470)	9.2% (533)	6.9% (1,236)	9.5% (670)
Boys (% (N))	51.4% (589,062)	50.8% (2,185)	51.7% (2,544)	51.4% (2,979)	51.6% (9,204)	51.8% (3,657)
Major birth defect (% (N))	3.3% (38,194)	3.9% (167)	3.5% (173)	3.3% (190)	3.5% (617)	3.6% (254)

% are column percentages

N = number

Q = quartile

Table 2. Specific neurological drugs associated with sperm damage and their adjusted odds ratios (AORs) for having at least one major birth defect. All liveborn singletons Denmark 1996-2016, and excluding births where mothers used any of the investigated drug at any time prior to birth. Odds ratios and p-values adjusted for birth year, paternal age, income and education, and maternal age, smoking status and education. Separate models per drug. Exposure taken as binary: having at least one prescription in the three month preconception timeframe. Offspring numbers for the sibling analysis include exposed as well as unexposed offspring.

Drug class	Number of offspring	Number of fathers	Birth defects	AOR	95% CI
Antipsychotics (N05A)	4,301	-	3.9% (167)	1.07	0.92 to 1.25
-after exclusion	2,590	-	3.3% (85)	0.95	0.77 to 1.18
-sibling analysis	5,437	1,971	3.4% vs 3.2%	1.00	0.74 to 1.37
Anxiolytics (N05B)	4,918	-	3.5% (173)	1.07	0.92 to 1.24
-after exclusion	3,153	-	3.2% (102)	1.03	0.85 to 1.26
-sibling analysis	6,196	2,379	3.4% vs 3.1%	1.08	0.82 to 1.43
Hypnotics and sedatives (N05C)	5,797	-	3.3% (190)	0.96	0.83 to 1.12
-after exclusion	3,706	-	3.2% (119)	0.99	0.83 to 1.19
-sibling analysis	8,478	3,220	3.1% vs 3.2%	0.97	0.76 to 1.25
Diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH)	1,633	-	4.7% (76)	1.22	0.97 to 1.54
-after exclusion	902	-	4.1% (37)	1.13	0.81 to 1.57
-sibling analysis	2,220	812	4.1% vs. 3.2%	1.24	0.76 to 2.02
Benzodiazepine-derived anxiolytics (N05BA)	4,742	-	3.5% (166)	1.06	0.91 to 1.24
-after exclusion	3,047	-	3.2% (97)	1.02	0.83 to 1.25
-sibling analysis	5,885	2,266	3.3% vs 3.1%	1.06	0.79 to 1.41
Benzodiazepines as hypnotics and sedatives (N05CD)	1,153	-	3.1% (36)	0.96	0.69 to 1.34
-after exclusion	736	-	2.9% (21)	0.93	0.60 to 1.43
-sibling analysis	1,495	545	2.9% vs 3.4%	0.88	0.49 to 1.59
(Benzo)diazepines grouped (N05AH, N05BA or N05CD)	7,057	-	3.6% (254)	1.06	0.93 to 1.20
-after exclusion	4,428	-	3.3% (147)	1.03	0.87 to 1.22
-sibling analysis	8,777	3,318	3.3% vs 3.3%	1.02	0.80 to 1.29
Antidepressants (N06A)	17,827	-	3.5% (617)	0.97	0.89 to 1.05
-after exclusion	11,487	-	3.2% (372)	0.95	0.85 to 1.05

-sibling analysis	23,400	9,020	3.3% vs 3.6%	1.02	0.87 to 1.19
SSRIs (N06AB)	11,902	-	3.3% (397)	0.94	0.85 to 1.04
-after exclusion	7,751	-	3.3% (254)	0.96	0.85 to 1.09
-sibling analysis	15,971	6,220	3.2% vs. 3.6%	0.93	0.77 to 1.11

Table 3. Eurocat subgroups (binary: ≥1) by drug class, all liveborn singletons, liveborn singletons, Denmark 1996-2016. Notice that offspring may appear in more than one category. Publication of numbers smaller than 5 not permitted. Classified as recommended in Eurocat Guide 1.4, section 3.3, pages 92-96.

Birth defect category	None of the specified drugs (1,147,055)	Antipsychotics (4,301)	Anxiolytics (4,918)	Hypnotics and sedatives (5,797)	Antidepressants (17,827)	(Benzo)diazepines (7,349)	N05AH (1,633)
Digestive	0.22% (2,471)	0.28% (12)	0.12% (6)	0.19% (11)	0.19% (33)	0.16% (11)	0.37% (6)
Urinary	0.26% (3,020)	0.37% (16)	0.33% (16)	0.38% (22)	0.29% (51)	0.40% (28)	0.73% (12)
Heart	0.70% (8,069)	0.77% (33)	0.79% (39)	0.78% (45)	0.70% (125)	0.79% (56)	0.73% (12)
Chromosomal	0.11% (1,283)	≤0.12% (≤5)	≤0.10% (≤5)	≤0.09% (≤5)	0.11% (20)	≤0.07% (≤5)	≤0.30% (≤5)
Limb	0.93% (10,699)	0.93% (40)	0.96% (47)	0.67% (39)	0.94% (167)	0.91% (64)	1.16% (19)
Nervous	0.11% (1,305)	0.19% (8)	0.14% (7)	0.16% (9)	0.08% (15)	0.13% (9)	≤0.30% (≤5)
Eye	0.12% (1,384)	≤0.12% (≤5)	0.14% (7)	≤0.09% (≤5)	0.12% (22)	0.11% (8)	≤0.30% (≤5)
Genital	0.25% (2,825)	0.21% (9)	0.22% (11)	0.24% (14)	0.30% (54)	0.24% (17)	≤0.30% (≤5)
Oro-facial clefts	0.15% (1,684)	0.19% (8)	≤0.10% (≤5)	0.16% (9)	0.13% (23)	0.11% (8)	≤0.30% (≤5)
Other	0.64% (7,287)	1.05% (45)	0.92% (45)	0.79% (46)	0.80% (142)	0.91% (64)	1.29% (21)

Table 4. Minimum risks detectable as abberant. Based on a univariate binomial model with population risk of 3.3% assuming a 1:10 exposed:unexposed ratio. The two rightmost columns assume a 50-50 mix between the population risk of 3.3% and the risk among the exposed.

Drug class	N	Minimum detectable odds ratio			
		Assuming 100% therapy adherence		Assuming 50% therapy adherence	
		80% power	90% power	80% power	90% power
Antipsychotics (N05A)	4,301	1.25	1.32	1.51	1.64
Anxiolytics (N05B)	4,918	1.25	1.28	1.51	1.57
Hypnotics and sedatives (N05C)	5,797	1.22	1.25	1.45	1.51
Diazepines, oxazepines, thiazepines and oxepines (as antipsychotics, N05AH)	1,633	1.45	1.54	1.90	2.10
Benzodiazepine-derived anxiolytics (N05BA)	4,742	1.25	1.28	1.51	1.57
Benzodiazepines as hypnotics and sedatives (N05CD)	1,153	1.54	1.64	2.10	2.31
(Benzo)diazepines grouped (N05AH, N05BA or N05CD)	7,057	1.19	1.22	1.38	1.45
Antidepressants (N06A)	17,827	1.13	1.16	1.25	1.32
SSRIs (N06AB)	11,902	1.16	1.19	1.32	1.38

Statistical appendix to: Nervous system drugs taken by future fathers and birth defects in offspring: a registry-based cohort study

Statistical appendix

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Introduction and summary

Since some observations were partially missing, either because they were treated as such (see below), or, mostly, because they were missing in the original dataset, we planned to impute those observations before running generalized additive models on the imputed datasets, and combine the results through Rubin's rule. At the moment of imputation, we had variables such as gestational age, smoking status of the mother, and education of both parents, as well as a large number of binary variables for drug exposures. We had 973 drugs which at least one father was prescribed during the three months preconception, 945 drugs that at least one mother was prescribed during the first trimester of pregnancy, and 885 drugs that at least one mother was prescribed during the rest of pregnancy. We also had various indicator covariates for maternal and paternal conditions, as well as 14 subgroups of birth defects (for example birth defects of the heart, etc.). Because imputation on all these covariates was impractical giving computational limitations, we set up the following approach.

1. We ran a lasso algorithm on the complete cases, from which we selected an appropriate set of variables to impute from for each of the variables that had missing data.
2. We ran multiple imputation by chained equations, imputing each of the missing value of a variable based on variables selected by the lasso algorithm for the variable of interest.
3. We ran logistic regressions with the logit link function through generalized additive models based on entire datasets after imputing all missing values and pooled the results through Rubin's rule.

The lasso algorithm used linear relationships only and no interactions were considered. For multiple imputation and logistic regressions, we used approaches that allowed a maximum of flexibility with regard to departures from linearity. In particular, for imputation we used predictive mean matching for numeric variables and simple indicator variables for each group of categorical variables (without further assumptions such as the proportional odds assumption), while for the logistic regressions we used scatterplot smoothers (thin plate splines with four knots spaced uniformly, i.e. the default setting of the statistical software – changing to cubic splines did not change the results) for numeric variables and again simple indicator variables for each group of categorical variables. Details are given below.

Data preparation and missingness

This analysis concerns liveborn singletons only. Birth lengths below 21 cm (often 0 cm or 10 cm, 8412 births) or above 69 cm (538 births) were treated as missing. Birth weights below 366 g (often 0 g or 100 g, 2091 births) and above 6583 g (63 births) (+/- 5 standard deviations) were treated as missing. At least master-level education was relabeled as high education. Education ranging from upper secondary to bachelor level was relabeled as middle education. Primary and lower secondary education were relabeled as low education. This relabeling was based on divergent trends of preconception drug use in this data set published elsewhere (reference 3 of the main manuscript). Education not elsewhere classified was treated as missing (1883 and 3669 births for father and mother, respectively). Maternal smoking was relabeled as no smokers, current smokers, and quit during pregnancy (thus collapsing the various moments of quitting during pregnancy).

After applying exclusion criteria, i.e. for observations used in the final analysis, we had the following numbers of missing data:

Supplementary Table 1. Numbers (%) of data missing for each variable that had at least one missing entry (% missing = 0 for all other variables). Smoking status of the mother was missing most often (8.4%), but had a negligible effect on birth defects. Education of the mother (3.4%) and father (3.8%) was missing next most often, with education of the mother having a small but highly significant effect (adjusted odds ratio on the order of 1.07, depending on the model).

Variable	**Number missing net of exclusion criteria**
Apgar score	8,531 (0.8%)
Birth length	13,001 (1.2%)
Birth weight	5,594 (0.5%)
Hospital days upon birth	6,015 (0.5%)
Disposable income father	4,818 (0.4%)
Education father	41,895 (3.8%)
Education mother	37,314 (3.4%)
Smoking status mother	92,448 (8.4%)
At least one variable missing	168,871 (15.3%)

Notice that while Apgar score, birth weight and length, and number of hospital days were not involved in the main analysis, they had to be imputed because other imputations might rely on them. For the same reason we initially imputed the 27,080 missing gestation ages.

Lasso

For the lasso algorithm, all numeric variables were standardized by subtracting the mean and dividing by twice their standard deviation. Binary variables were not standardized. To allow for convergence in reasonable time, we first selected even years only, after which we sampled without replacement 1 in every 5 observation, giving approximately 10% of the original data or some 100 thousand (100K) observations. On this reduced dataset we then ran the lasso cross validation algorithm of R package *glmnet* (version 4.0-2), i.e. cv.glmnet() with alpha=1. From the cross validation results (representative example in Figure 1), we selected an appropriate number of variables from which to impute.

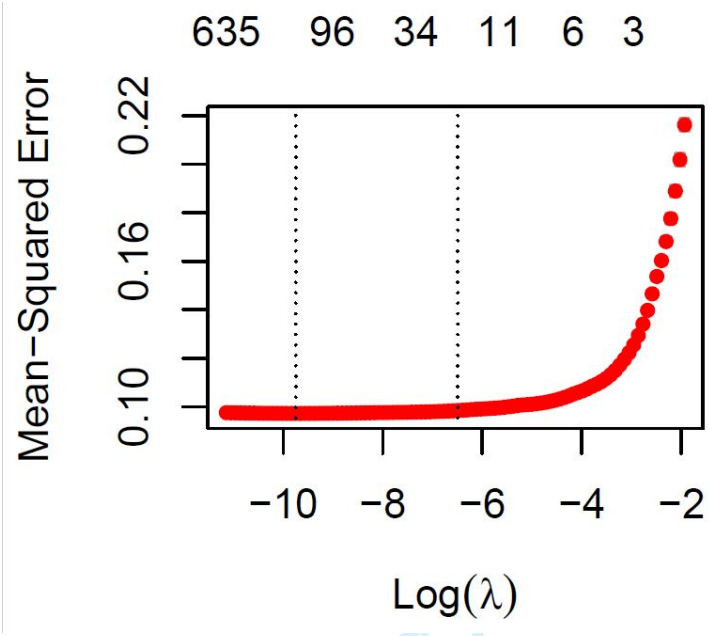

Figure 1. An example of a lasso result, in this case of gestation age on a sample of 100K observations. On the x-axes the number of non-zero covariates (top) along with the log of the penalty parameter λ (bottom). The loss (mean squared error) is given as the y-axis. Observe that the null model (0 covariates) corresponds to imputing the mean, giving a MSE (≈variance) of 0.25 as a result of our standardization procedure. After log(λ) reaches -6, diminishing returns lead the addition of further covariates to reduce the mean squared error only marginally, whereas the number of variables with non-zero coefficients grows swiftly. In this case we selected a model with 75 variables, striking the middle between sparsity and accuracy (see main text of this Appendix).

In selecting the set of variables to impute from, we considered that we had the following reasons to be generous, i.e., likely to choose a high number of variables:

1. A better, fuller model gives more accurate imputations and so improves the precision of estimates.
2. The relationships in the complete cases may differ somewhat from the relationships in the whole population (if we knew all missing values). Selecting a generous model gives a chance for these relationships to be picked up in the imputation procedure.
3. There would have been some sampling variability in selecting 100K observations from the dataset, in which the relationships may differ somewhat from the remaining (complete cases) dataset. Selecting a generous model gives a chance for this relationship to be picked up in the imputation procedure.
4. Overfitting was not our first concern, since we wished to maximally capture the variability in the data and our sample size is large relative to the number of variables.
5. We had particular reason to be generous for those variables with a high percentage of observations missing (smoking status in particular), so that *ceteris paribus* gains from accurate imputations would be larger (although variability in variables used in those imputations may also propagate).
6. Selecting a small model may lead imputations to depend on variables that are missing at the same time, which little opportunity to seize on other information in the data.

We also had the following reasons to be conservative, i.e. choose a low number of variables:

1. A small model runs faster, which was the aim of the lasso screening step. Multiple imputations based on the entire dataset is too slow and unnecessary.
2. Since there is variability in sampling the subset on which to run lasso, the variables near the minimum loss (the left vertical dashed line in Figure 1) may not be relevant for the rest of the data.

3. Some of the non-zero coefficients in the selected lasso model may not be at their full, unpenalized values. Removing the restriction of penalization may increase the predictive power of the model in the multiple imputation setting without need for additional covariates in the imputation model.

In practice we ended up choosing a model halfway between lambda for the minimum loss (lambda.min) and lambda at one standard error of the minimum loss (lambda.1se). Up to 50 covariates were added to the latter model depending on the location of lambda.min, the amount of missing data, a visual inspection of the plateau, and any pre-existing knowledge on the status of a variable as a confounder, always staying well away from lambda.min. The exceptions to this procedure were the education factor variables, which did not converge on 100K observations. For these variables we divided up the 100K variables in 4 datasets (of 25K variables each), ran the lasso algorithm on each of these, selected the lambda.min model for each, and took the intersection of the four sets of covariates. Hence, the first selection was generous (large number of variables selected), but taking the intersection of the four sets is conservative (small number of variables selected). For education, this procedure gave 59 variables for the father and 105 for the mother. Smoking status of the mother was imputed from 146 variables due to high missingness. The other variables were imputed from much smaller models (11-16 covariates). Thus, we used large models for variables with a relatively large amount of missing data, or that were difficult to predict.

Multiple imputation

Multiple imputation was done using chained equations (Gibbs sampler) under the assumption of missingness at random, implemented in R package *mice* (version 3.8.0) with a custom made predictor matrix set up from the models found through the lasso procedure outlined above. We created 10 imputed datasets using polytomous regression without further assumptions for categorical variables and predictive mean matching for numerical variables. The number of imputed datasets was lower than the 15% suggested by the "one dataset for each percent of missing data" rule, justified because most variables had only low percentages of missing data, and were used only indirectly. Because the default number of 5 iterations suggested that convergence was perhaps not fully achieved for some variables, we ran 10 iterations. Convergence was achieved after 7 iterations.

Logistics regressions (generalized additive model)

We ran logistic regression fully adjusted for birth year, paternal characteristics, and maternal characteristics, as implemented in R package *mgcv* (version 1.8-33). For example,

```
model<-gam(birth defect ~ drug name + s(birth year) +
                education father + s(income father) + s(age father) +
                education mother + smoking status mother + s(age mother),
                data = data,
                subset = liveborn singletons after exclusion criteria,
                family = binomial()
)
```

The scatterplot smoothers used most degrees of freedom for birth year and age mother, and least for income and age father.

Such models were run in functions that ran them for each of the datasets, pooled the estimates, and summarized the results, as implemented in R package *mice*:

estimates <- with(data = data, gam as above *omitting the data statement*)

pooled estimates <- pool(estimates)

model results <- summary(pooled estimates)

STROBE Statement—Checklist of items that should be included in reports of ***cohort studies***
Please find the places in the manuscript of each item indicated in red.

	Item No	Recommendation
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract This is done both in the title (page 1) and the abstract (page 2).
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found Done (abstract, page 2).
Introduction		
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported Done in the first two paragraphs of the introduction (page 4).
Objectives	3	State specific objectives, including any prespecified hypotheses Third (and last) paragraph of introduction (page 4).
Methods		
Study design	4	Present key elements of study design early in the paper The study design is already alluded to at the beginning of the third paragraph of introduction (page 4).
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection Setting, locations and relevant dates are given in the first paragraph of the methods section, bottom of page 4, top of page 5. Exposure is defined in the subsection with that name, bottom of page 5, top of page 6. Follow-up is given in the subsection called "outcome", below the middle of page 5. Data collection not relevant as we used registry data.
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up Elegibility criteria, sources, and methods of participant selection are all given in the "data and inclusion criteria" subsection of methods, bottom of page 4, upper half of page 5. Methods of follow-up (in our case: in the registry) is given in the subsection called "outcome", below the middle of page 5.
		(*b*) For matched studies, give matching criteria and number of exposed and unexposed Not applicable (not matched)
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable Outcomes and exposures are addressed in the respective subsections of the methods section alluded to above. Potential confounders are discussed in the first paragraph of the subsection called "Statistical analyses", lines 126-132. Effect modifiers were not analyzed.
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group We have described for each source, which variables that source yielded ("Data and inclusion criteria", pages 4-5).
Bias	9	Describe any efforts to address potential sources of bias As these are registry data, bias is presumably limited, although visibility to the healthcare system may be an issue. This is mentioned in the discussion, "strengths and

		limitations", page 9.
Study size	10	Explain how the study size was arrived at See first paragraph of results section, "the cohort", page 7.
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why First paragraph of "Statistical analyses", page 6. No groupings were made.
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding First paragraph of "Statistical analyses", page 6. Details on GAMs in Statistical Appendix.
		(*b*) Describe any methods used to examine subgroups and interactions Also "Statistical analyses", page 6, second paragraph (lines 133-136).
		(*c*) Explain how missing data were addressed Please see subsection "missing data" on page 6, as well as the detailed Statistical Appendix.
		(*d*) If applicable, explain how loss to follow-up was addressed Not applicable.
		(*e*) Describe any sensitivity analyses Page 6, lines 134-135.
Results		
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed See first paragraph of results section, "the cohort", page 7.
		(b) Give reasons for non-participation at each stage Not applicable.
		(c) Consider use of a flow diagram We have considered this, but the cohort is relatively straightforward.
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders Table 1 is dedicated to this, discussed in the second paragraph of the first section of the results (page 7).
		(b) Indicate number of participants with missing data for each variable of interest This is summarized in the Statistical Appendix.
		(c) Summarise follow-up time (eg, average and total amount) All offspring were followed-up for one year (in the registry) as stated in the "outcome" subsection of methods.
Outcome data	15*	Report numbers of outcome events or summary measures over time All tables give the absolute numbers the analysis is based on.
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included Crude rates are given in Table 1 (last row); adjusted odds ratios (along with crude rates) are given in Table 2. Confounders as specified above.
		(*b*) Report category boundaries when continuous variables were categorized Not applicable.
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period Not relevant because we did not find an elevated risk.
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and

		sensitivity analyses Table 2 shows how exclusion by maternal criteria changes the results (or rather, how it does not).
Discussion		
Key results	18	Summarise key results with reference to study objectives Discussion, first paragraph, bottom of page 8, top of page 9.
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias Discussion section "strengths and limitations" (page 9) is dedicated to this.
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence Discussion section "Interpretation, possible mechanism, and comparison with literature" (pages 9-10) is dedicated to this.
Generalisability	21	Discuss the generalisability (external validity) of the study results See discussion, page 9, first paragraph of "Interpretation, possible mechanism, and comparison with literature".
Other information		
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based Page 3, "funding".

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at http://www.strobe-statement.org.